

# Bounds on effective Majorana neutrino masses at HERA

M. Flanz<sup>a</sup> \*, W. Rodejohann<sup>a</sup> †, K. Zuber<sup>b</sup> ‡

<sup>a</sup>Lehrstuhl für Theoretische Physik III,

<sup>b</sup>Lehrstuhl für Experimentelle Physik IV,

Universität Dortmund, Otto-Hahn Str. 4,

44221 Dortmund, Germany

## Abstract

The lepton-number violating process  $e^\pm p \rightarrow \nu_e(\bar{\nu}_e)l^\pm l'^\pm X$  mediated by Majorana neutrinos is studied for the HERA collider for  $(ll') = (e\tau)$ ,  $(\mu\tau)$ ,  $(\mu\mu)$  and  $(\tau\tau)$ . Only the muonic decay of the  $\tau$  is considered. The direct limit on the effective muon Majorana mass,  $\langle m_{\mu\mu} \rangle$  is improved significantly to  $4.0 \cdot 10^3$  GeV and for the first time direct limits on the analogous effective masses connected with the tau sector are given, namely  $4.2 \cdot 10^3$  GeV for  $\langle m_{e\tau} \rangle$ ,  $4.4 \cdot 10^3$  GeV for  $\langle m_{\mu\tau} \rangle$  and  $2.0 \cdot 10^4$  GeV for  $\langle m_{\tau\tau} \rangle$ . We find that a more general analysis for an upgraded HERA could improve this values by a factor of up to 40, yet still being orders of magnitude worse than indirect limits.

lepton-hadron processes; massive neutrinos; mass bounds; Majorana neutrinos

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\*Email address: flanz@dilbert.physik.uni-dortmund.de

†Email address: rodejoha@dilbert.physik.uni-dortmund.de

‡Email address: zuber@physik.uni-dortmund.de

# 1 Introduction

Since there is growing experimental evidence [1] of nonzero neutrino masses using neutrino oscillations as explanations [2], an additional fundamental question still to be solved is the character of the neutrinos, i. e. are they Dirac or Majorana particles? From the theoretical side the latter case is favored since Majorana particles pop out of almost every GUT [3] and are also the product of the attractive see-saw-mechanism [4]. The most important tool to answer this question is the detection of lepton-number violation in the neutrino sector. The most effort of theoretical and experimental work has been put in neutrinoless double beta decay ( $0\nu\beta\beta$ ), resulting in an upper limit on the effective Majorana mass  $\langle m_{ee} \rangle = |\sum U_{em}^2 m_m \eta_m^{\text{CP}}|$  of about 0.2 eV [5], where  $m_m$  are the mass eigenvalues,  $\eta_m^{\text{CP}} = \pm 1$  the relative CP parities and  $U_{em}$  the mixing matrix elements. In general, there is a  $3 \times 3$  matrix of effective Majorana masses, the elements being

$$\langle m_{\alpha\beta} \rangle = \left| \sum U_{\alpha m} U_{\beta m} m_m \eta_m^{\text{CP}} \right| \text{ with } \alpha, \beta = e, \mu, \tau. \quad (1)$$

For sake of simplicity we assume that the elements  $U_{\alpha m}$  are real and skip also  $\eta_m^{\text{CP}}$ . Only few direct information on elements other than  $\langle m_{ee} \rangle$  is available: muon-positron conversion in sulfur gives a limit on  $\langle m_{\mu e} \rangle \lesssim 0.4$  (1.9) GeV, when the final state proton pairs are in a spin singlet (triplet) state, respectively. This limit is obtained when comparing the theoretical value from [6] with the PDG branching ratio limit [7] and using the fact that the matrix element of the process is proportional to  $|\langle m_{\mu e} \rangle|^2$ . In a recent paper [8] we considered the reaction  $\nu_\mu N \rightarrow \mu^- \mu^+ \mu^+ X$ , mediated by Majorana neutrinos, and deduced a limit of  $\langle m_{\mu\mu} \rangle \lesssim 10^4$  GeV, improving the previous bound [9] by one order of magnitude. To our knowledge, there are no direct limits on other elements of  $\langle m_{\alpha\beta} \rangle$ . Note that we are considering direct limits, i. e. using processes sensitive on the respective quantity. Indirect bounds, obtained from oscillation experiments and unitarity of the mixing matrix will of course be far more restrictive.

In this paper we will study the process

$$e^\pm p \rightarrow \nu_e^{(-)} l^\pm l'^\pm X, \text{ with } (ll') = (e\tau), (\mu\tau), (\mu\mu) \text{ and } (\tau\tau) \quad (2)$$

for the case of the HERA collider. We will focus mainly on the  $e^+p$  mode, but the qualitative conclusions we draw remain of course valid for  $e^-p$ -collisions as well. We demand the taus<sup>1</sup> to decay in muons to take advantage of the like-sign lepton signature, which is more unique for muons than electrons. A further effect is to have a small number of like-sign ( $e\mu$ ) or ( $ee$ ) events, which might be more background dominated. The relevant diagram for process (2) is shown in Fig. 1.

It is evident that such a process has a spectacular signature with large missing transverse momentum ( $\not{p}_T$ ) and two like-sign leptons, isolated from the hadronic remnants. Direct production of heavy Majoranas  $N$  at HERA has been studied before [10] with the process  $e^-p \rightarrow XN \rightarrow XW^\pm l^\mp \rightarrow X\nu l'^\pm l^\mp$  resulting in two leptons with different charge. In

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<sup>1</sup>We shall use the term electron, muon or tau for both, particle and antiparticle.

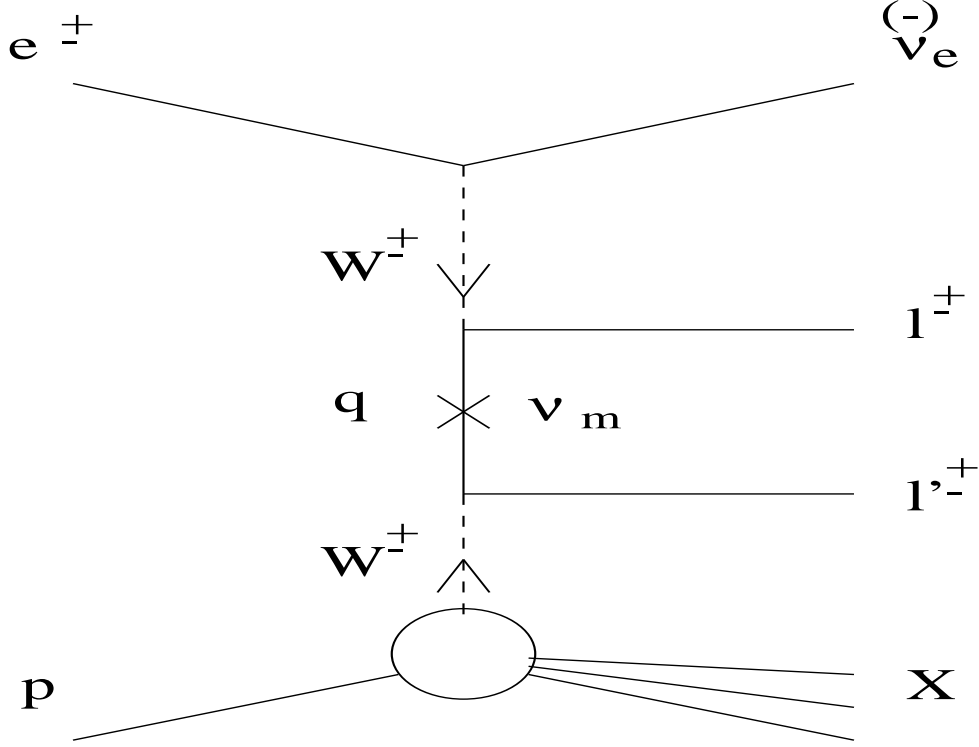


Figure 1: Feynman diagram for the process  $e^{\pm} p \rightarrow \bar{\nu}_e^{(-)} l^{\pm} l'^{\pm} X$ .  $q$  denotes the four-momentum of the propagating Majorana neutrino. Note that there is a crossed term and for  $l \neq l'$  two possible assignments for the corresponding lepton vertex exist.

contrast to direct production the process discussed in the present paper deserves some attention because of its unique signature.

## 2 Analysis

We use HERA kinematics for electron and proton energies  $E_e = 27.5$  GeV,  $E_p = 820$  GeV and the GRV 98 [11] set of parton distributions. To mimic the experimental situation the following kinematical cuts are applied:  $|\eta_{l,X}| \leq 2.0$  and  $|\vec{p}_T| \geq 10$  GeV. Here  $|\vec{p}_T| = \sqrt{(\sum p_x^\nu)^2 + (\sum p_y^\nu)^2}$  is the total missing transverse momentum, with the sum going over all neutrinos, i. e. one neutrino for the  $(\mu\mu)$ , three for the  $(e\tau)$  and  $(\mu\tau)$  and five for the  $(\tau\tau)$  case.  $\eta_{l,X} = -\ln \tan(\theta_{l,X}/2)$  is the pseudorapidity of the charged lepton  $l$  and the hadronic final state  $X$  respectively, with  $\theta$  the polar angle in a system where the  $z$ -axis is parallel to the proton direction. In addition, we want the charged leptons to be isolated from the hadrons and demand  $\Delta R = \sqrt{(\phi_l - \phi_X)^2 + (\eta_l - \eta_X)^2} > 0.5$  with  $\phi$  being the azimuthal angle.

The exact calculation of the diagram and some general features of the resulting cross section are described in [8]. For the problem at hand we additionally folded in the three-body decay of the tau leptons. When considering heavy neutrinos, one has to note the mixing of the usual standard model (SM) leptons with these hypothetical particles. The Lagrangian for the lepton  $l$  coupling to neutrino mass eigenstates  $\nu_m$  is:

$$\mathcal{L} = \frac{g}{\sqrt{2}} \sum_m U_{lm} \bar{l} \gamma_\alpha \gamma_- \nu_m W^\alpha + \text{h. c.} \quad (3)$$

This leads to a dependence of the cross sections of the form:

$$d\sigma(ep \rightarrow \nu_e ll' X) \propto \left| \sum U_{lm} U_{l'm} \frac{m_m}{q^2 - m_m^2} \right|^2 \quad (4)$$

with  $q$  being the four-momentum of the propagating Majorana neutrino.

The DELPHI collaboration [12] examined the mode  $Z \rightarrow \bar{\nu}_l \nu_m$  and found a limit of  $|U_{lm}|^2 < 2 \cdot 10^{-5}$  for masses up to  $m_m \simeq 80$  GeV and  $l = e, \mu$  and  $\tau$ . For larger masses analyses of neutrino-nucleon scattering and other processes yielded [13]

$$\sum |U_{em}|^2 < 6.6 \cdot 10^{-3}, \quad \sum |U_{\mu m}|^2 < 6.0 \cdot 10^{-3} \quad \text{and} \quad \sum |U_{\tau m}|^2 < 1.8 \cdot 10^{-2}. \quad (5)$$

### 3 Results and Discussion

In Fig. 2 the total cross section as a function of *one* mass eigenvalue  $m_m$  is shown for all combinations of final state charged leptons, without considering the above mentioned  $U_{lm}$  limits (i. e. setting  $|U_{lm}|^2 = 1$ ). Our condition that the tau decays into a muon is included. As can be seen, there is a maximum at about 70 GeV, which has purely kinematical reasons, see [8]. This means that we can assume one eigenvalue dominating the sum  $\sum m_m^2 (q^2 - m_m^2)^{-2}$ . For small masses the cross section rises with  $m_m^2$  and for higher masses it falls with  $m_m^{-2}$  as can be understood from the two extreme limits of  $m_m^2 (q^2 - m_m^2)^{-2}$ . The masses of the final state leptons have almost no effect (less than 5 %), so that the only numerical difference comes from the branching ratios (BR), the  $U_{lm}$  limits from Eq. (5) and the factor 2 for the  $(e\tau)$  and  $(\mu\tau)$  cases. The latter comes from the two possible assignments the two leptons have, when emitted from the Majorana vertex.

These limits combined with the branching ratio  $\text{BR}(\tau \rightarrow \mu \nu_\mu \nu_\tau) = 0.1732$  [7]) lead to a maximal cross section of about  $10^{-23}$  b in the  $(\mu\mu)$  case for a neutrino mass of 80 GeV. It is about 12 orders of magnitude smaller than the SM charged current (CC)  $e^+p$  cross section of  $\sigma_{\text{CC}}(e^+p, Q^2 > 200 \text{ GeV}^2) \simeq 30$  pb [14] (we checked that the  $Q^2$  condition is not significantly violated for the cuts we applied). Nevertheless the above cross section is some orders of magnitude closer to the relevant SM CC process than most other exotic Majorana neutrino induced  $\Delta L = 2$  processes such as  $K^+ \rightarrow \pi^- \mu^+ \mu^+$  [15] or  $\mu^- \mu^+$ -conversion via muon-capture in  $^{44}\text{Ti}$  [16]. These have ratios with respect to the relevant SM CC process of at most  $10^{-20}$ . For  $\nu_\mu N \rightarrow \mu^- \mu^+ \mu^+ X$  a ratio of  $10^{-17}$  [8] for a 500 GeV neutrino beam is achieved, so the process described here results in an improvement of another 5 orders of

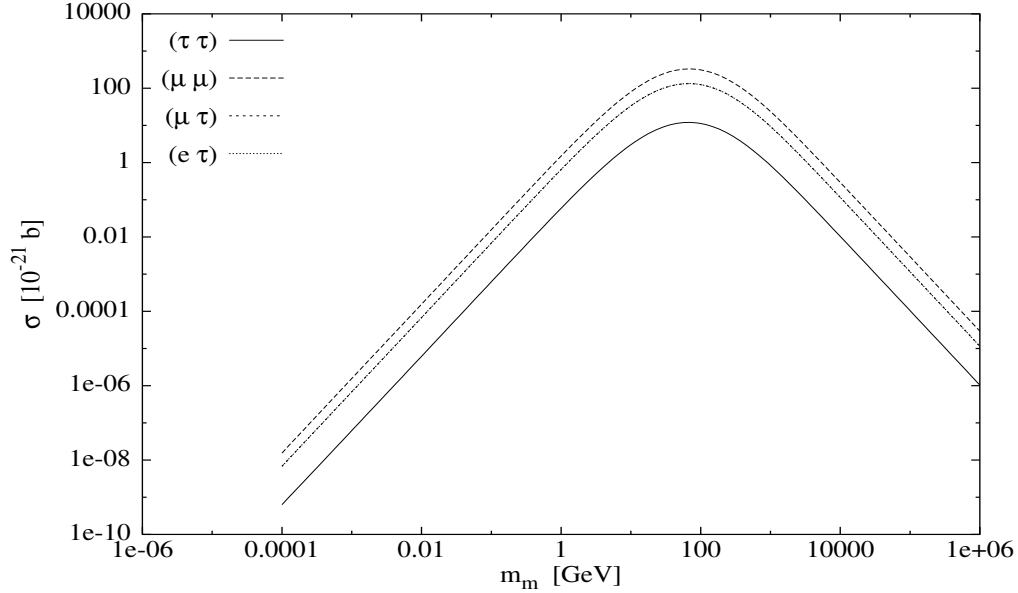


Figure 2: Total cross section for  $e^+p \rightarrow \bar{\nu}_e l^+ l'^+ X$  as a function of *one* eigenvalue  $m_m$ . No limits on  $U_{lm}$  are applied, the branching ratio for taus into muons is included. The  $(e\tau)$  and  $(\mu\tau)$  cases are indistinguishable in this plot.

magnitude.

The  $e^-p$  mode gives (in contrast to the normal CC process) a cross section *smaller* than for  $e^+p$  by a factor of about 2 (1.9 for small masses, 2.5 for masses higher than  $10^2$  GeV), so that the ratio for this mode is a factor 4 worse. The other cases, like  $(\tau\tau)$ , have ratios with respect to the SM CC process maximally one order of magnitude smaller than the  $(\mu\mu)$  case.

As an example for differential cross sections we plot in Fig. 3 for  $m_m = 80$  GeV the distribution of the missing transverse momentum for the  $(\mu\mu)$ ,  $(\mu\tau)$  and  $(\tau\tau)$  case. Note that all these cases have two like-sign muons in the final state. The mean values are  $\langle p_T \rangle \simeq 28.3, 37.0$  and  $37.3$  GeV, respectively. The shape is different for each case, despite the similar mean value of missing transverse momentum. To distinguish, say,  $(\mu\tau)$  from  $(\tau\tau)$  events, one should consider other distributions, e. g. the invariant mass of the two muons,  $m(2\mu)$ , as displayed in Fig. 4. Whether a muon comes directly from the Majorana vertex or from the tau-decay makes its energy and momenta fraction of the total available energy smaller and changes its invariant mass. Here the mean values are  $\langle m(2\mu) \rangle \simeq 66.8, 28.1$  and  $16.1$  GeV, for  $(\mu\mu)$ ,  $(\mu\tau)$  and  $(\tau\tau)$ , respectively. Unfortunately, this procedure requires high statistics. On an event-by-event analysis detailed kinematic reconstruction as well as angular distributions might be more useful.

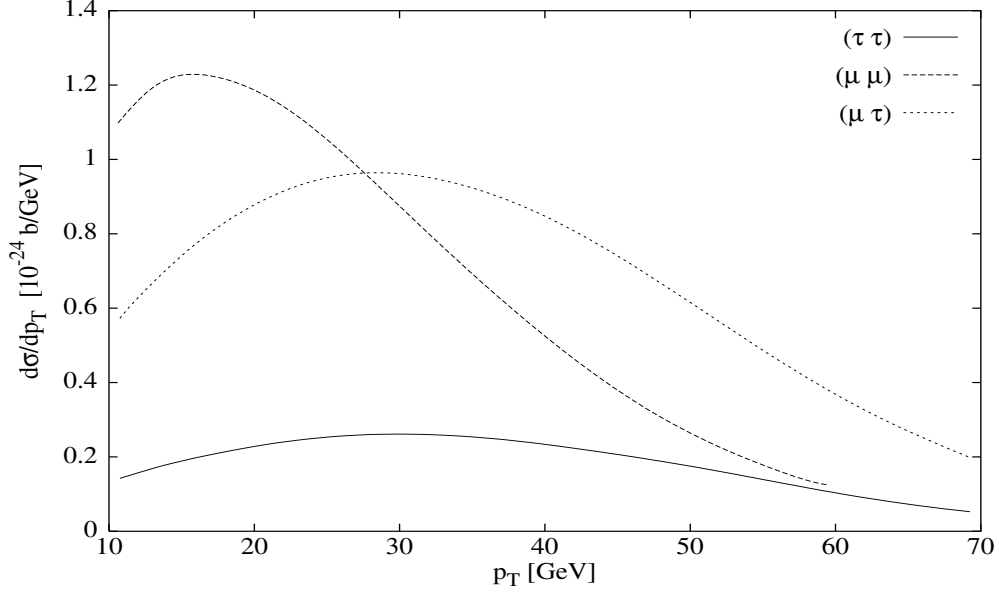


Figure 3: Distribution of the total missing transverse momentum  $p_T$  for the  $(\mu\tau)$ ,  $(\mu\mu)$  and  $(\tau\tau)$  case in the reaction  $e^+p \rightarrow \bar{\nu}_e l^+ l'^+ X$  for  $m_m = 80$  GeV. In order to have the curves in the same order of magnitude we did not include the tau branching ratio.

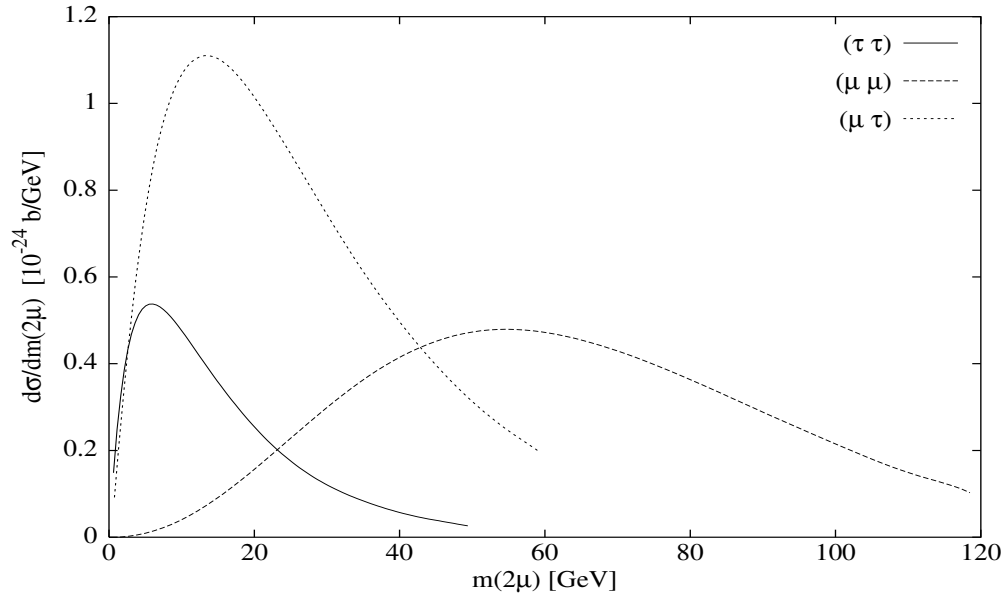


Figure 4: Invariant mass distribution for the two like-sign muons given for the same parameters as in the previous figure.

Because of its lepton-number violating character the discussed process should be background free from standard model processes. On the other hand, misidentification of the muon charge might create some like-sign dimuon events. Processes producing opposite sign muon pairs are pair production of heavy quarks, photon-photon interactions,  $Z$ -boson production, Drell-Yan pairs from resolved photon-proton interactions, pion punchthrough associated with a single muon event and beam related background. Practically all these processes can be eliminated by kinematical arguments. Therefore the identification of two like-sign, isolated muons with large  $p_T$  in addition to a large missing transverse momentum should indeed be an outstanding signature. For the  $(e\tau)$  channel, which has a like-sign  $e\mu$  signature, single  $W$  production [17] is a severe background. However, sophisticated kinematical arguments as those given in [10] for the case of direct Majorana production might be also applicable in the case discussed here. Because of this we shall assume zero background, leaving a more detailed analysis for further studies. In case of observation such a detailed analysis has to be done anyway in order to rule out any standard model process as the ones described above.

In order to get bounds for  $\langle m_{\alpha\beta} \rangle$  we assume that the cross sections displayed in Fig. 2 are proportional to  $|\langle m_{\alpha\beta} \rangle|^2$  and take the luminosities used in searches for isolated lepton events with missing transverse momentum, i. e.  $\mathcal{L}_{e^+} = 36.5 \text{ pb}^{-1}$  (H1, [18]) and  $\mathcal{L}_{e^+} = 47.7 \text{ pb}^{-1}$  (ZEUS, [19]). We take the average of  $42.1 \text{ pb}^{-1}$  and get values in the range of  $10^3$  to  $10^4 \text{ GeV}$ , thereby improving the  $\langle m_{\mu\mu} \rangle$  limit with respect to [8] significantly and giving for the first time direct limits on  $\langle m_{\alpha\tau} \rangle$ . Combining all limits, ignoring possible phases in the elements  $U_{\alpha m}$  (therefore getting a symmetrical matrix  $\langle m_{\alpha\beta} \rangle$ ) as well as skipping the intrinsic CP parities, the following direct bounds for the effective Majorana mass matrix exist:

$$\langle m_{\alpha\beta} \rangle = \begin{pmatrix} \langle m_{ee} \rangle & \langle m_{e\mu} \rangle & \langle m_{e\tau} \rangle \\ & \langle m_{\mu\mu} \rangle & \langle m_{\mu\tau} \rangle \\ & & \langle m_{\tau\tau} \rangle \end{pmatrix} \lesssim \begin{pmatrix} 2 \cdot 10^{-10} & 0.4 (1.9) & 4.2 \cdot 10^3 \\ & 4.0 \cdot 10^3 & 4.4 \cdot 10^3 \\ & & 2.0 \cdot 10^4 \end{pmatrix} \text{ GeV}. \quad (6)$$

A spread over 14 orders of magnitude can be seen. We state again that these are direct limits and the elements other than  $\langle m_{ee} \rangle$  should not be confused with their real values. As is evident and not surprising, the bound coming from  $0\nu\beta\beta$  is by far the best limit for an effective Majorana neutrino mass. One might argue that FCNC processes like  $\tau \rightarrow \mu\gamma$  place severe bounds on this effective masses. Applying the BR from [20] to the measured limits from [7, 21] gives bounds for  $\overline{m_{\alpha\beta}} = \sqrt{\sum U_{\alpha m} U_{\beta m} m_m^2}$  of the order 1 to a few 10 GeV. Without specifying to a special mass and mixing scheme it is rather difficult to compare  $\langle m_{\alpha\beta} \rangle$  with  $\overline{m_{\alpha\beta}}$ . Since there is no commonly accepted scheme around, we believe that numbers derived from experiments are necessary. Another point is that in principle one could derive the remaining elements of  $\langle m_{\alpha\beta} \rangle$  from the limits on  $\langle m_{e\mu} \rangle$  and  $\langle m_{ee} \rangle$ . Here the same argument holds. One should say that if the value for  $\langle m_{ee} \rangle$  is fixed, all other elements of  $\langle m_{\alpha\beta} \rangle$  should be in the same order of magnitude, therefore at most a few eV. Our matrix (6) is thus far from being physically realized.

The factor of about 3 the  $(\tau\tau)$  limit is worse is due to our condition that only the tau decay

into muons is considered, which could be skipped in a more general analysis including more decay channels. Note that with our assumption  $\sigma \propto \langle m_{\alpha\beta} \rangle^2$  the bound is proportional to  $\sqrt{1/\sigma\mathcal{L}}$ . Therefore a general treatment of all possible tau decay channels would bring a factor of about 5.8 for  $(\tau\tau)$  and 2.4 for the channels involving only one tau. Furthermore, an optimistic luminosity value of  $1 \text{ fb}^{-1}$  would bring another factor of about 5.

An upgraded HERA with  $E_p = 1020 \text{ GeV}$ ,  $E_e = 33.5 \text{ GeV}$  rises our cross sections for the small mass regime by about 60 %, so that with an integrated luminosity of  $1 \text{ fb}^{-1}$  and in consideration of all tau channels our bounds could thus be lowered by a factor of 40.

## 4 Conclusions

We have studied the Majorana neutrino induced process  $e^\pm p \rightarrow \bar{\nu}_e^{(-)} l^\pm l'^\pm X$  at HERA and deduced for the first time direct bounds on all effective Majorana masses other than the one measured in  $0\nu\beta\beta$ . A way to distinguish signal events from each other as well as from background is discussed. We propose a search for two like-sign muons in the final state combined with large missing transverse momentum. The cross sections are typically 12 to 13 orders of magnitude smaller than SM CC processes, which has to be compared with related rare meson decays or  $\mu^- \mu^+$  conversion on nuclei, which give ratios of at most  $10^{-20}$ . We improved the direct limit on  $\langle m_{\mu\mu} \rangle$  significantly and gave for the first time direct limits on  $\langle m_{e\tau} \rangle$ ,  $\langle m_{\mu\tau} \rangle$  and  $\langle m_{\tau\tau} \rangle$ . However, these are direct bounds, which will be orders of magnitude worse than ones derived indirectly.

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